

# Performance Analysis of Routing Algorithms in AANET with Realistic Access Layer

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**Abstract.** Aeronautical Ad-hoc NETWORKs (AANETs) have been studied and could be proposed as an complementary communication system for civil aviation. Several routing algorithm have been proposed and assessed through simulation, but there is a lack of evaluation in realistic conditions, especially regarding the access layer. In this paper we propose to use Random Packet CDMA (RP-CDMA) as a MAC layer protocol for AANETs. We then present the results of simulations with actual aircraft trajectories considering successively three well-known routing algorithm (namely AODV, DYMO and BATMAN). We conclude from these simulations that AODV has the best performances, but also that the realistic access layer is quickly saturated by the mere signalization traffic. This calls for improvements in both routing algorithms and access layer.

**Keywords:** AANET · Ad-hoc · Network · Routing · RP-CDMA

## 1 Introduction

AANETs are ad-hoc networks in which the nodes are civil aircraft in flight. They are a subset of Mobile Ad-hoc NETWORKs (MANETs) and share properties with the Vehicular Ad-hoc NETWORKs (VANETs) [1].

In the future, AANETs could enable new peer-to-peer services for en-route aircraft such as wind-networking [2] or automatic conflict resolution [3].

In the short term however, only traditional communication systems such as satellite links and HF DL (High Frequency Data Link) are available to commercial aviation in oceanic and remote areas. Because of this, most of the currently used services are designed to use a air-ground communication system, as in [4]. In consequence, AANETs are considered in the middle term as a complementary solution to air-ground communication systems [5], and this paper will focus on air-ground communications.

As in any multihop network, a routing algorithm is required to determine the end to end path for each packet. Numerous protocols have been proposed for AANETs (e.g. ARPAM [6], AeroRP [7], greedy forwarding [8] ...), and they

have been evaluated against classical routing algorithms in simulations (AODV for the two given examples). However, to our knowledge, none of these protocols was assessed against real aircraft trajectories with an appropriate and realistic access layer model. The goal of this paper is to present the results of simulations of selected classical routing algorithms on replayed aircraft trajectories, with a realistic access layer model. These algorithms have been well studied, and are often used as a reference to compare the performances of other routing algorithms. We want here to explore their performances in realistic AANET simulations.

This paper is organized as follow: related work is presented in Sect. 2, the protocols and their adaptation to our case are described in Sect. 3. The experimental settings are described in Sect. 4 and the results are presented in Sect. 5 then discussed in Sect. 6. Our conclusion (Sect. 7) summarizes our findings, and future works are described in Sect. 8.

## 2 Related Work

Most of VANETs studies rely on the use of either 802.11 access layer or an ideal access layer. Simulations with an ideal access lack of realism, and 802.11 link layer was not primarily designed for ad-hoc networks, especially when ranges exceed 300 km [9]. The access layer used in this paper is based on the following work, specifically tuned for AANETs.

In [9], the author advocates for the use of Code Division Multiple Access (CDMA), but uses a static code allocation, under the hypothesis that enough codes are available to give one to each aircraft. This solution was tested for AANETs, with real aircraft trajectory but an ideal routing module.

RP-CDMA is a code allocation mechanism proposed in [10], in which the spreading codes are randomly selected for each transmission (see Description in Sect. 3.1). RP-CDMA offers the best performances when used with partitioned spreading, an interference cancellation method.

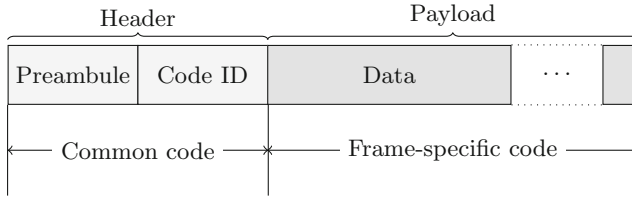
RP-CDMA has been augmented with link layer functionalities in [11], and tested in an ad-hoc environment.

## 3 Protocols Used

### 3.1 Access Layers

**Description.** RP-CDMA solves the problem of code attribution inherent to CDMA access layer in an elegant and simple way. The payload of an RP-CDMA frame is spread with a randomly chosen code, and an identifier for this code is included in the header. The header contains a preamble in order to improve packet detection and synchronization, and the code ID is spread with a code, common to every header (cf. Fig. 1).

This frame structure provides channel separation between signalization (headers) and the data (payload). If the pool of payload codes is big enough, RP-CDMA is mainly limited by header collisions.



**Fig. 1.** Base structure of a RP-CDMA frame.

Several techniques are available to detect the payload and recover their collisions. Amongst them, Partitioned Spreading (PS) offers the best performances [10]. PS is also resistant to the near-far effect, one of the biggest limitations to other CDMA systems. Near-far situations are encountered when the difference in received power between two colliding frames is so high that the processing gain isn't enough to decode both frames.

In [11], the authors add MAC and LLC functionalities to the base RP-CDMA. Access control is performed in a way similar to non-persistent CSMA, with the addition that several messages can be transmitted at the same time.

The added LLC services are acknowledgement, automatic retransmissions and integrity control. These requires to add some fields to the base RP-CDMA frame: sender and destination addresses, CRC and frame ID. In order to reduce header collision probability, these fields are added to the section of the frame spread with the frame-specific code. Payload length and coding rate are also added to the header in [11].

**Modelisation.** We modeled RP-CDMA with the following assumptions:

- When two header collide, both frames are considered unrecoverable.
- If there are less than  $maxPayload_{rx} - 1$  other frames colliding simultaneously with a given payload, this payload can be decoded. Otherwise, it is not recoverable [10].
- If the distance between a sender and a receiver is above  $range$ , the frame is not taken into account.

In [9], the author demonstrate that a radio range of 350 Km is enough to have an average connectivity over 90 % and provides a link budget for this range. Based on this publication and on results in [10], we have used the following values:  $maxPayload_{rx} = 25$ ,  $range = 350$  km and  $bitrate = 800$  kb/s.

After an adaptation of the work presented in [10] to the context of AANETs, the header length of the RP-CDMA frame header was set to 80 bits, and the RP-CDMA fields spread with the specific code use to 102 bits.

The access layer modules uses FIFO queues to store pending packets. These queues can hold 100 packets, and they drop any new packet received from upper layer when this limit is reached.

**Optimization for AANETs.** Several parameter of the MAC layer can be tuned to adapt the MAC layer to our specific case, namely:

- $maxFrame_{tx}$ : number of frames that a node can send simultaneously.
- $backoff$ : the backoff duration of the non-persistent CSMA (expressed in header duration).
- $ackTimeout$ : the time to wait before resending a frame if no acknowledgement is received.

These parameters have been optimized through simulations, the metrics, observed at the link layer, were:

- Success ratio: ratio of the volume of data passed to upper layer to the volume of data received from upper layer.
- Delay: delay between the queuing of a packet in a MAC module and its reception by the receiver’s MAC module.
- Efficiency: ratio of the volume of data passed to upper layer to the volume of data sent by the radio module.

In the simulations, 53 nodes (the maximum number of neighbors in 99% of the time in real aircraft trajectories) are randomly positioned in a 350 Km radius disk, each node generating a constant bit rate UDP traffic toward a center node, and the center node generating a similar traffic toward each node.

Several batches of simulation were run, modifying only one of the three parameter at a time. After each batch, the best value for this parameter is kept and used in the next batch of simulation. The independence of each factor is checked by the absence of influence between the behavior of one parameter and the value of the others. The following values have been obtained after this campaign of simulation:  $maxFrame_{tx} = 1$ ,  $backoff = 100$ ,  $ackTimeout = 50$  ms. The success ratio obtained with these values is presented in Fig. 2.

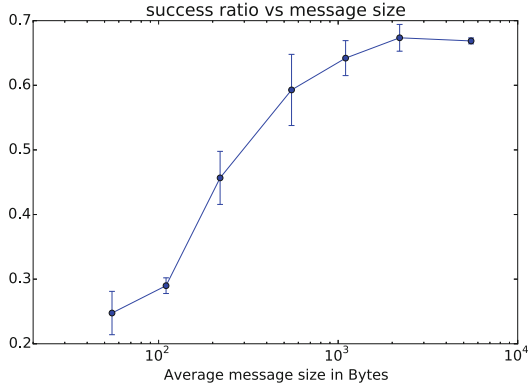
### 3.2 Routing

The routing protocols used in this paper were chosen because they are typical examples of two families of routing protocols: reactive protocols with AODV and DYMO, and proactive protocols with BATMAN.

Because of the profile of the traffic and the positions of the nodes, we expect to see data traveling along long routes toward and from ground stations. AODV and DYMO seems both well suited this setting because they let intermediary node construct routing table toward both ends of a route during route resolution, which renders unnecessary any later route resolution between the intermediary node and the ground station. DYMO, with its path accumulation, is expected to reduce even more the required route resolutions.

BATMAN is an effective proactive routing algorithm. It has been preferred over OLSR because of its better scalability [12].

We have selected these classic routing algorithms because their performances have been widely studied in a variety of networks, and we want to extend this knowledge in the context of AANETs with realistic conditions. We describe in this section the general working principle of each of these routing protocols.



**Fig. 2.** Success ratio of the MAC layer after optimization campaign (generated load:  $0.5 \times$  channel capacity)

**AODV.** Ad-hoc On demand Distance Vector (AODV [13]) is a reactive routing algorithm which performs route discovery on demand, and handles route maintenance while they are in use.

Route discovery is performed when a packet is generated and there is no route entry toward its destination. A “route request” packets (RREQ) is broadcasted to the whole network, in a flood-like manner. Any node records from which neighbor this request was received and, if it has a fresh route entry toward this destination, sends a “route reply” packet (RREP) to the originator of the request. Nodes which are relaying this RREP learns by the way a route toward the destination. Because AODV uses symmetric links (e.g. to transmit RREP), a mechanism involving periodic “hello” messages is used to detect neighbors reachable through a symmetric link. Broken links are detected in the same way, and they trigger the sending of a route error message (RERR).

AODV features a rate limitation for control messages: no more than 10 control messages can be sent per second. However, given the geographic positions of the aircraft in our scenario, there is sometimes a significant amount of aircraft that could not be reached (e.g. flying alone on a remote route). In consequence, if the ground station tries to reach every aircraft, it will keep sending RREQ even though they are doomed to fail, these request being repeated while there are messages to send. This constant flow of control messages can reach the rate limit in the nodes close to ground stations, so any further control message is dropped, including RREQ which could succeed. In order to mitigate this issue, the traffic generation is initiated by aircraft, and ground stations only replies to it, thus preventing the constant flow of RREQ from the ground station.

**DYMO.** The Dynamic MANET On-demand routing protocol (DYMO, [14]), also called AODVv2, is a derivative of AODV. It uses the same mechanism of RREQ and RREP. The main difference is that DYMO implements a “path accumulation” feature: each node forwarding a RREQ/RREP can add its own address

in the header of the packet. Thus, when the RREQ reaches the destination (resp, the RREP reaches the originator), the destination (resp. originator) learns not only the route toward the destination (resp. originator), but also toward every other node on the route. This potentially reduces the required number of route resolution and control packets in the network. Another difference is that it does also not use the “hello” messages from AODV, relying instead on received RREQ and RREP to detect broken links.

**BATMAN.** In BATMAN (Better Approach To MANet routing, [12]), each node broadcasts regularly a small message, called an “Originator Message” (OGM), which is then flooded in the whole network. This OGM contains the originator address, and the originator sequence number. This sequence number is increased after each sending of an OGM, and is used by the nodes receiving this OGM to keep track of already received OGMs.

Each node receiving the OGM records its sequence number, originator address, and the address of the neighbor node that just sent it. It then uses a ranking procedure to give a rank to this neighbor as a next-hop toward this originator, then uses the highest-ranked neighbor to define the route toward this originator.

The period of sending of the OGMs is a critical parameter, as it controls the refresh rate of the routing information, but also the amount of signaling data generated. If it is low few control packets will be generated, so the network consumption will be low, but the routes will take time to be refreshed, leading to more routing errors. A faster sending rate will keep the routes more up to date, but will increase signaling.

This value was optimized for case of AANETs. Several simulations have been run for different values of this period under a low aircraft density scenario. The value of 5 s minimized the delay and reachability, and is used in the simulations presented in this paper.

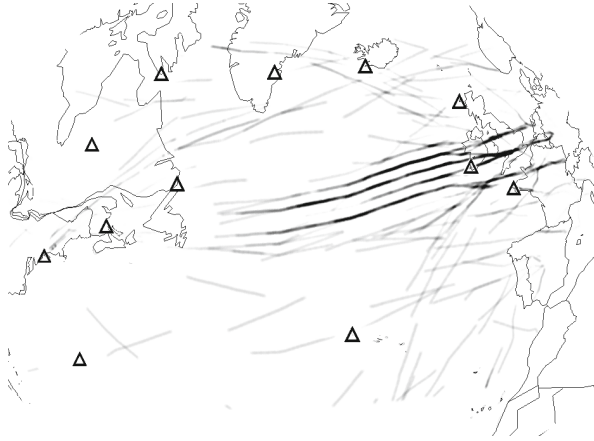
## 4 Experimental Setting

### 4.1 Simulation Environment

The simulations were conducted in the simulator OMNeT++ [15], based on the INET framework [16]. The model nodes were using INET’s module for the protocols AODV, DYMO, BATMAN [17], UDP and IP, and custom modules for the traffic generation and node mobility.

### 4.2 Node Positions

In our study, we focused on the North Atlantic Tracks (NAT) [5] as an example of structured air traffic. We used real aircraft position data from Eurocontrol historical traffic repository, tailored to our study case, as an input to our simulations [18].



**Fig. 3.** Aircraft density on the 2014-05-02, 8 h to 9 h time slot (greyscale). Ground station are presented as black triangles.

In MANET, protocol performances does not depend only on node density, but also on node spatial distribution [19]. In order to take this into account, we used real traffic data. Several different days were re-played to add statistic diversity to the aircraft positions while using real geographic data.

Because of the computational cost of the simulation, we had to restrict the simulations to a set of representative time slots. In this paper, we present the results of simulation conducted on the 8 h to 9 h time slot, for the 2013-09-14, 2014-05-02 and 2015-05-15. These dates present the median number of aircraft per day for their year, and the 8 h to 9 h time slot corresponds to a medium Instantaneous Aircraft Count (IAC) during the day. Furthermore, this time slot correspond to the end of the eastbound traffic flow, and the beginning of the westbound flow, which is the time of the day during which the topology of the network seems to vary the most.

In order to match the different possible air routes and hence maximize the probability of delivery, twelve ground stations were placed on land masses around the area of interest (see Fig. 3).

### 4.3 Traffic Generation

The traffic generation is designed to trigger a minimum response from the reactive routing algorithms, and acts also as a probe to measure several metrics. It mimics the communication between inflight aircraft and air traffic management authorities on the ground. Because one of our goals is to assess the “base” network consumption for each algorithm, this traffic is kept as low as possible.

It consists in periodic UDP message (data messages) exchanged between aircraft and ground. When a data message is received, an acknowledgement is sent (another UDP message). In order to handle the rate limit problem of AODV

(cf. AODV in Sect. 3.2), ground stations do not initiate these communications, they start sending data messages to a given aircraft only when it is actually reachable (i.e. the ground station has received messages from it).

The period of sending is low enough in order to keep the route active to prevent route expiration in the case of reactive algorithm. In our simulations it was set to 1 s, and the size of the data generated is 9 bytes.

Given the size of the network (up to 600 simultaneous nodes), the computations are slow (simulation speed as low as 0.01 simulated seconds per runtime seconds were attained under our experimental setting), which prevents us from publishing here results of higher load study. The results presented here show nevertheless the “base network consumption” for these routing algorithms.

#### 4.4 Metrics

**Delay.** The one-way end-to-end transmission delay is measured with the UDP packets, and recorded in an histogram.

**Reachability.** We define reachability as the ability to exchange messages bidirectionally between a host and a ground station. It is measured by sending a probe packet and waiting for its acknowledgement. If this acknowledgement is received within a given time (*ackTime*), the node is considered reachable. The node is considered unreachable when no acknowledgment packet is received in time. This is measured with the probe packets sent by the traffic generator module and their acknowledgements. Previous simulation with an ideal access model (i.e. without loss, and with a delay equal to the sum of propagation and transmission delays) have shown that the one-way delay was lower than 1 s for 98 % of the packets. We thus set *ackTime* to 3 s in this study, large enough to ensure that the measured losses of reachability do not correspond to the “ideal” delay, and small enough to provide a sensible value in regard of the requirements of actual services [4].

In the actual topology of our network, some subset of the nodes can not be reached because they are too far from any other nodes, however good the routing algorithm is. In order to take this into account and remove this bias from the measure, the reachability values are normalized against the “connectivity to the ground” (connectivity has here the meaning used in graph theory).

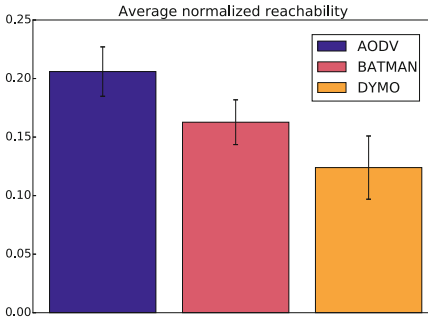
Let  $\mathbf{G} = (\mathbf{A} \cup \mathbf{S}, \mathbf{E})$  be the graph representing our network. The vertices  $\mathbf{A}$  are the inflight aircraft and  $\mathbf{S}$  the ground stations, and the edges  $\mathbf{E}$  are the possible ideal links (i.e. there exists a link when two aircraft are closer than 350 km in our case). Let  $N_p$  be the number of aircraft in  $\mathbf{A}$  for which there exists a path to a ground station. We define the “connectivity to the ground” as  $C = \frac{N_p}{|\mathbf{A}|}$ .

**Network Routing Load.** The network load due to the routing signalization is measured by counting routing packets passed from IP modules to MAC modules.

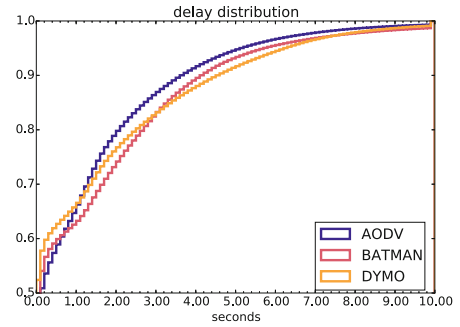


## 5 Results

On every graph in this paper, error bars represent 95 % confidence interval.



**Fig. 4.** Average normalized reachability. (Color figure online)



**Fig. 5.** Cumulative density function of end to end delay. (Color figure online)

The average normalized reachability is presented in Fig. 4. From this graph, we can conclude that AODV performs significantly better than DYMO. Given the uncertainty associated to BATMAN, we can say that the latter performs between AODV and DYMO with respect to reachability.

The Fig. 5 represents the histogram of one-way end to end delay for each protocol. The delay obtained for AODV is the lowest for the last 30 % of the distribution.

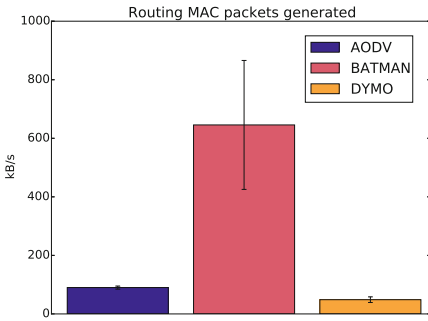
The amount of signaling generated by each protocol, presented in Fig. 6, follows the expected pattern. BATMAN generates significantly more routing control messages than AODV, which generates significantly more signaling than DYMO. This graph shows only the generated signaling volume, the data rate measured at the MAC layer ranges from 54 kB/s (DYMO) to 70 kB/s (AODV).

The packet hop count histogram, presented in Fig. 7, shows AODV carries a higher ratio of packets on longer routes.

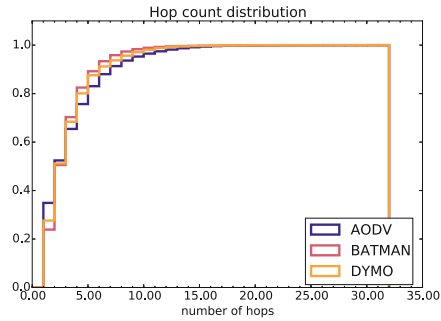
## 6 Discussion

The low values of reachability in the Fig. 4 can be explained by the high delays observed in Fig. 5: roughly 28 % of the packet takes more than 1.5 s to reach their destination. This very high delay is due to the congestion of the access layer queues in the vicinity of the ground stations. This congestion also leads to packet drops when the queues are full, which further decrease the probability that a probe packet (or its response) reaches its destination.

BATMAN signaling is one order of magnitude above AODV and DYMO because, as a proactive protocol, it maintains routing information toward every node in the network. With BATMAN, the load generated by each node is proportional to the square of the number of node in the same connected subnet



**Fig. 6.** Generated control data. (Color figure online)



**Fig. 7.** Hop count distribution. (Color figure online)

(connected as in graph theory) because it rebroadcasts every OGM it receives. So when the network is partitioned, the amount of signaling packets sent by each node is reduced by the square of the size reduction of each subnet, which leads to a great variation in the load generated by BATMAN, hence the wide confidence interval. The reactive protocols generate less signalization than BATMAN and, as expected, DYMO generates less control packet than AODV.

The data in Fig. 7 also explain the better results of AODV in terms of reachability, because it allows further nodes to be reached. Compared to DYMO, AODV features indeed an active broken link detection mechanism (“hello” messages), which leads to faster route error detection and repair. On a long route, a broken link is more likely to occur, so the speed of its detection has more impact on the average success ratio of packets on this route. If this error is detected quickly, packets arriving from far nodes suffer less from this effect. This explains why AODV shows a higher proportion of large hop counts than DYMO. The same “long route” effect explains also why AODV has a higher hop count than BATMAN. Because BATMAN generates a higher MAC load in the whole network, the probability of loss because of MAC congestion is higher in overall, and it is more detrimental if the route is longer.

The poor absolute performance of the network presented here, must be considered with respect to the success ratio of the MAC layer presented in Fig. 2. Because the generated network traffic consists of small probe and signalization packets (on average less than 110 bytes), the MAC layer operates where it is less effective. In consequence, these results encourage for performing aggregation in the link layer in order to increase the size of the frames. Because the generated traffic was only made of probe packets, it is not meaningful to compare these absolute performances to classic communications systems such as satellite links and HFDL.

Independently of the absolute performances, these results show that AODV performs better than BATMAN and DYMO in terms of reachability. Even though AODV has a bigger overhead cost than DYMO, the reachability gain offsets this weakness.

Furthermore, we have also conducted simulations based on an ideal access layer, and their results confirm this trend (AODV performs better than BATMAN and DYMO).

## 7 Conclusion

We have assessed the behavior of three well-known routing algorithms dedicated to MANET in AANET simulations, with both a realistic access layer based on RP-CDMA and actual aircraft trajectories. Simulation results show that AODV is the best suited routing algorithms for our air-ground communication system based on an AANET. The changes to AODV brought by DYMO are detrimental in terms of reachability. And BATMAN is already overloading the access layers with the signalization traffic it generates, so it will not be scalable to a situation with more load or more nodes.

Even if AODV shows the best performances in term of reachability, delay and route length, this study confirms that, as the resources are scarce in AANETs, the development of frugal routing algorithms has to be considered.

## 8 Perspectives

We will address the problems illustrated in this paper in the following ways:

The RP-CDMA model will be improved by adding aggregation to the current MAC model to use it layer in its optimal performance domain.

Because considered routing algorithms signalization already overloads the access layers, the development a new frugal routing algorithm seems necessary. Geographic routing algorithm can make use of already existing system aboard aircraft (GPS positioning, ADS-B traffic monitoring...) in order to reduce the required signalization. We are currently validating and assessing an innovative routing algorithm derived from trajectory based forwarding [20], taking into account the actual aircraft density to create sensible packet trajectories without requiring exact route resolution.

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